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CIVIL AND MILITARY R&D SPENDING:
THE CASE OF NUMERICALLY CONTROLLED MACHINE TOOLS

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PREFACE

This paper on the numerically controlled (NC) machine tool industry is part of a broader study conducted by the RAND Graduate School's Civil and Military Technology Workshop led by Dick Neu. The class efforts were directed towards analyzing the relationship between research and development (R&D) investment in the military and civilian sectors of the U.S. economy. That is, we addressed the topic of how military R&D investments might have a synergistic or spillover effect upon the civilian economy, or relatedly, how military investments might be used to overcome existing market failures in dual military/civilian industries. Additionally, we looked for evidence to suggest that military investments have had a negative impact on civilian technological development, by crowding out civil investments and raising the market prices of inputs. Each student wrote a substantial case study of an industry to evaluate the government's role in its success or failure. Besides NC machine tools, the industries included airframes, parallel processing, the early development of computers, and semiconductors.

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I. INTRODUCTION

Machine tools are powered devices used to cut or form pieces of metal into a desired size and shape within specified tolerances and finishes. The majority of machine tools are used in metal-removal or forming processes to produce other machines or other products. Some of the most common types include lathes, milling and grinding operations, punching and shearing operations, and multi-tool/multifunction machining centers.

The case of NC machine tools is a particularly interesting one because of its colorful history and sometimes dismal performance. Most recently, the world machine tool industry gained notoriety in the Toshiba-Kongsberg technology transfer scandal. In April 1987, the Japanese Toshiba Machine Co. and the Norwegian arms manufacturer Kongsberg Vaapenfabrikk were found to have completed a $17 million sale of milling machinery and its numerical control units with the Soviet Union. This equipment was on the Coordinating Committee for Export Control's (COCOM) list of critical goods embargoed to Warsaw Pact countries. The milling equipment is used to grind submarine propellers that are more quiet than those the Soviets were previously able to produce, significantly setting back the United States' anti-submarine warfare (ASW) advantage over the USSR.[1]

U.S. machine tool production is a relatively small industry; 1986 machine tool production in the United States accounted for only $2.7 billion out of $4,235 billion in total GNP.[2] This is less than that of the U.S. paper bag industry.[3] The industry's 1987 employment totalled about 64,300. These figures reflect not only the industry's small size, but also its recent stagnation. In fact, its weakness warranted a 1986 plan for voluntary export restraint agreements with foreign producers, as well as subsidies to support machine tool R&D. President Reagan initiated these policies out of concern for the defense industrial base's ability to mobilize in time of war. Because machine tools are a crucial part of defense production, the industry is considered essential for defense readiness.

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[1]For more on the Toshiba-Kongsberg sale, see David E. Sanger. "Toshiba Details Trail of Crime in Sale of Machinery to Soviets," *New York Times* (10 September 1987): 1.

[2]Production and employment data compiled in Joseph Jablonowski, "Soviets Still Lead in Machine-tool Consumption," *American Machinist* 132 n. 2 (February 1988): 63. GNP data from *Economic Report of the President* (Washington, DC: GPO, 1988): 248.

[3]G.P. Sutton. *Technology of Machine Tools, Volume I: Executive Summary* (Livermore, CA: Lawrence Livermore Laboratory, October 1980): 1.

Conventional machine tools strongly rely upon skilled machinists to control the positioning and accuracy of cuts on each piece of metal. Numerical control of machine tools, however, significantly reduced this dependency. Essentially, numerical control provided a way of reducing skilled man-hour requirements in production by controlling the metal-removing or forming process through mathematical code. Numerical control can permit more accurate tolerances in each workpiece and quick flexibility in the production of small-batch jobs, and reduce the downtime of machine tools by as much as 70-80 percent.[4]

In 1949 the Air Force awarded the contract for the development of NC to defense subcontractor John Parsons. The Department of Defense (DoD) also assured the commercial viability of NC technology by procuring a significant proportion of the first NC machine tools. Other users of machine tools such as the automotive, civil aircraft and agricultural equipment industries later turned to NC once the technology became more cost effective.

This paper addresses the role military spending played in the development and evolution of NC machine tool production. Did DoD investments improve the economic well-being of Americans by giving the U.S. a head start in NC production? Or might the U.S. machine tool industry have been better off if NC technology had been introduced at a later point in time? What sort of economic market failures might DoD investment have helped overcome in the machine tool market? Or must we attribute government spending in this industry predominantly to national security concerns rather than taking on an industrial policy role?

The available data on these questions are rather inconclusive. The Air Force's early investment in numerical control did provide the United States with a 5-6 year head start in world NC machine production. Additionally, NC equipment has been a cornerstone for improved productivity in many U.S. industries. Furthermore, because of the machine tool industry's early atomistic structure and extreme cyclicality, the DoD may have provided capital to which firms would not have otherwise had access. However, sizable early procurements and stringent production specifications also provided machine tool builders with incentives to focus production on more specialized equipment rather than standard *commodity* machine tools, the market sector in which other countries now show significant world market shares.

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[4]Ralph G. Rapello. *Essentials of Numerical Control* (Englewood Cliffs, NJ: Prentice-Hall, 1986): 5.

The paper proceeds as follows. Section 2 outlines the history of NC development while Section 3 discusses some of the basic principles of NC. Section 4 provides a thorough discussion of the structure of NC machine tool production and its economic vicissitudes. Section 5 discusses the government's role in NC evolution while Section 6 examines the evidence of market failure in that industry. Finally, Section 7 discusses alternative paths the government might have taken in the NC industry, and draws conclusions about the role of military investment in R&D.

II. THE HISTORY OF NUMERICAL CONTROL

Numerically controlled machines operate by representing the designs for a machine tool's cutting path in numerical code which is subsequently translated into electrical signals. These signals, in turn, drive servomechanisms that run the machine tool. The extreme of machine tool automation is a flexible manufacturing system (FMS) whereby a plant's industrial equipment communicates with one another in the metal cutting, assembly and quality control processes. NC machine tools are the heart of computer-aided manufacturing (CAM) which, along with computer-aided design (CAD) techniques, has been touted as the key to overcoming the high cost of American labor and improving U.S. productivity.

Although machine tools have existed for several decades, the commercial development of numerical control only occurred shortly after the emergence of the computer. The earliest version of automatic control mechanisms can be traced to 1728 when Frenchman Joseph Jacquard built the Jacquard loom. It used a series of steel cards to direct when threads should be entered into a weaving scheme.[1] In 1863 the pianola or player piano was patented by M. Fourneaux. This device relied on a roll of holed paper through which air was blown to depress the piano's keys.[2]

A U.S. man named Scheyer applied for a patent in 1912 for his cloth-cutting machine device which "provided a means for controlling motion in any direction or space either in one plane or several for angular motion by means of a previously prepared record such as a perforated sheet of paper or other material."[3] This "record-playback" technique was further refined around 1946-47 by General Electric, Gisholt and some smaller firms.[4]

Tracer technologies were also developed in the 1930s and 1940s. These devices used templates or patterns which guided the cutting tool, thereby reproducing the pattern. However, both tracer technology and record-playback continued to rely upon skilled machinists, whose motions were either recorded or used to form templates. These control

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[1] Ibid., p. 2.

[2] Edward E. Kirkham. "Chapter 1: Genesis of Numerical Control," in Frank W. Wilson (ed.), *Numerical Control in Manufacturing* (New York: McGraw Hill, 1963): 3.

[3] Ibid., p. 4.

[4] David F. Noble. "Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools," in Andrew Zimbalist (ed.), *Case Studies on the Labor Process* (New York: Monthly Review Press, 1979): 22.

technologies were suitable for producing mass quantities of parts, but less useful when small to medium-size batches of a variety of parts were required.

The impetus for numerical control was twofold. First, the Air Force was concerned that tracer, record-playback, and conventional machine tools would not offer sufficient output and flexibility for aircraft production, particularly in time of industrial surge.[5] Second, the rising cost of wages and a shortage of skilled machinists convinced control designers to devise systems that would increase productivity per man-hour.[6]

The Emergence of NC

In 1949, John Parsons, an airframe subcontractor from Michigan, won a contract for the development of NC from Wright-Patterson AFB's Air Material Command. Parsons and his associate, Frank Stulen, had devised a two-axis control system for a milling machine using punched card tabulating equipment to form helicopter rotor blade airfoil patterns with accuracies far greater than had previously been achieved.[7]

Parsons subcontracted the development of the first NC machine tool's servomechanisms to the Massachusetts Institute of Technology's Servomechanisms Laboratory. In 1952, its efforts came together in a three-axis, vertical-spindle Cincinnati Hydrotel (hydraulic) milling machine, converted from tracer control. The mill was controlled by machine instructions in binary code on perforated tape. A picture of this first NC machine is shown in figure 2.1.

MIT received another AF contract in the mid 1950s for NC software development. The preparation of the NC perforated tapes which stored the cutter line path instructions appeared to be one of the most difficult problems limiting the technology's economic viability. Originally, the NC programs were produced manually in binary code, but later MIT researchers employed their first digital computer, the Whirlwind.

In 1956, an MIT mathematician named Douglas Ross created a skeleton programming system to be combined with more specific directions for cutting tools. This FORTRAN-based system was known as Automatically Programmed Tools, or APT. It was found to be particularly useful by the Air Force because of its flexibility, its applicability to virtually every machine tool. Also, APT met the AF's specifications for up to five-axis

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[5]Kirkham, p. 4.

[6]"Chapter 2: Machine Tools and Their Control," *Modern Machine Shop 1988 NC/CIM Guidebook* 60 n. 8A (January 1988): 52.

[7]For a more thorough history of Parson's work, see "Chapter 1, Numerical Control: What's It all About," *Modern Machine Shop 1988 NC/CIM Guidebook* 60 n. 8A (January 1988): 44-46.

control. Because of its versatility, the Air Force and the Aerospace Industries Association (AIA) agreed to adopt APT as the industry standard, accompanied by post-processors to match the program to the configuration of each machine tool.

NC technology was first produced abroad by Great Britain in 1957 and France in 1958, but by 1959, most other countries of Western Europe were also producing it. However, NC machine tools were not produced commercially in Europe until 1960 and growth in their sales did not take off until 1964.[8] Japan originally lagged behind both Europe and the United States in NC production. It first began developing NC technology from the early 1960s onward, but production was not at an industrial scale until 1965. Today, West Germany and Japan have surpassed the United States in terms of total machine tool production.

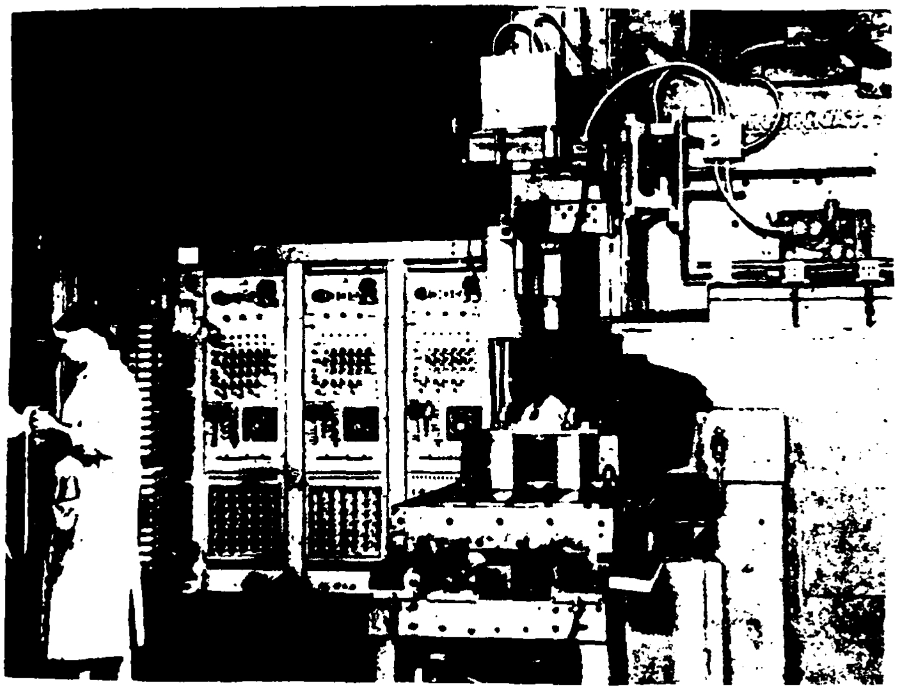

Fig. 2.1—The First NC Machine Tool

Source: Robert S. Woodbury. *Studies in the History of Machine Tools* (Cambridge, MA: MIT Press, 1972): 101.

[8]Data on the origins of European and Japanese NC production are from OECD. *NC Machine Tools, Their Introduction in the Engineering Industries* (Paris, 1970): 39-41. Foreign competition is discussed in more detail in Section 4.

III. HOW MACHINE TOOLS AND NC WORK

Machine tools are characterized by: 1) their relative motion to the workpiece, and 2) the position of the spindle relative to the work surface. The diagrams in figure 3.1 show some examples of relative motion between the tool and the workpiece. In some circumstances, the workpiece itself is rotated while the cutting tool passes along its length--the basic motion of a lathe. Other times the workpiece is passed along the rotating tool, as with a mill or grinding machine.

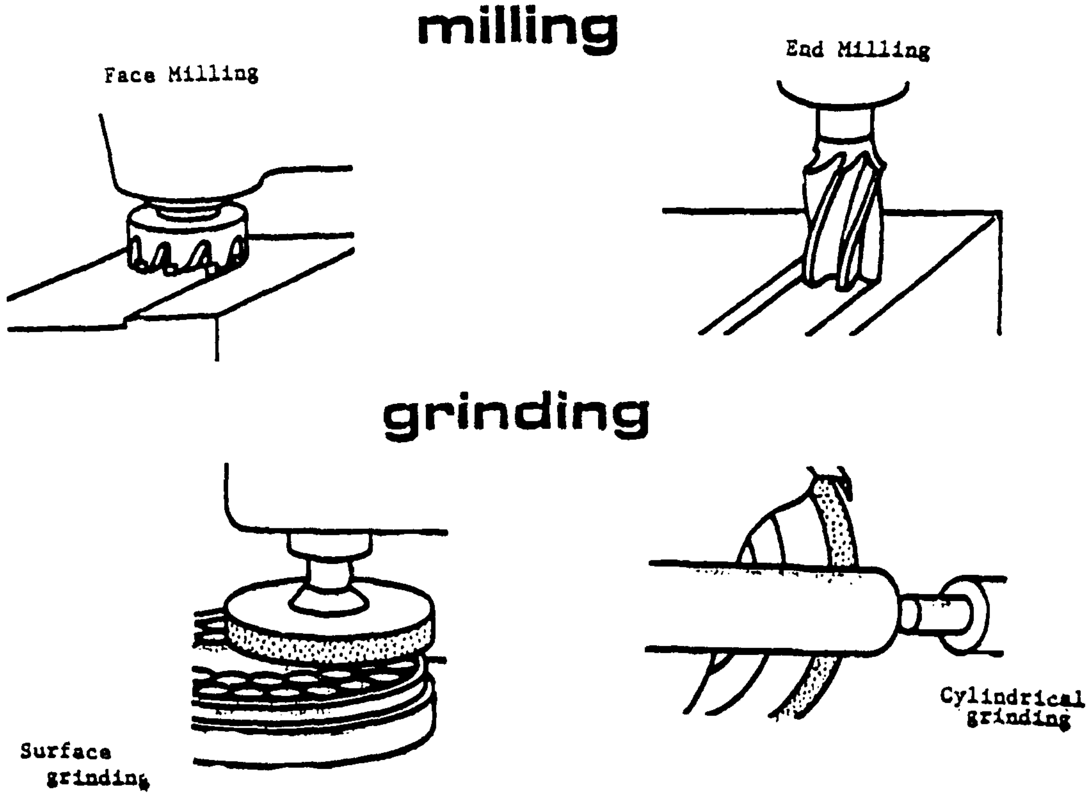

Fig. 3.1—Two Types of Relative Machine Tool Motion

Source: International Trade Commission (hereafter ITC). *Competitive Assessment of the U.S. Metalworking Machine Tool Industry* (Washington, DC: U.S.ITC Publication 1428, September 1983): 150-151.

Additionally, machine tools are categorized as *horizontal* or *vertical* by the position of the tool spindle relative to the work surface. All machine tools have their cutting tool

positioned perpendicular to the work surface. In some cases, metal chips fall directly on the machine bed or in the cutter path if the spindle is positioned vertically. Therefore, some machine spindles have a horizontal orientation to take advantage of gravity.

Numerical control also brought with it the *machining center.* Machining centers do a number of tooling operations by automatically changing tool bits in the machine spindle. These multifunction machines usually store their cutting tools, which can number above 90, in a storage magazine. The machine control unit (MCU) directs a tool to be loaded and the spindle correctly repositioned in front of the work surface.

Standards for Machining Axes

Machine tools are also categorized by their number of axes, or linear and rotary motions. Both the Electronics Industries Association and the Aerospace Industries Association base their standards for the naming of these axes on the right-hand rule of coordinates, whereby the positive direction of an axis is designated from the base of the finger to the tip. Positive rotary motion is clockwise when observing it from the base of the finger to the tip .

Among the three dimensions of linear motion, the Z axis is always designated to be the axis of main spindle travel. The axis of the longest travel perpendicular to Z is designated X. Therefore, for a vertical spindle drilling machine, the Y axis would be that movement across the width of the workpiece. A horizontal spindle drilling machine's Y axis would signify vertical travel.[1] Axes A, B and C designate rotary motion around X, Y and Z respectively. Other axes are designated as secondary or tertiary linear and rotary motions parallel to the primary axes.

Control Unit Characteristics

Numerical control uses three dimensional Cartesian coordinates to direct the cutter tool's movements, with zero specified as the point of intersection of the X, Y and Z axes. Each machine tool's MCU converts the program into actual machine movements, providing instructions for the servomechanisms. Virtually all MCUs were hard-wired from NC's inception in the early 1950s through the early 1970s, physically limiting crucial functions of the machine tool. With the rise of minicomputers, however, modern MCUs have become much more versatile.

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[1]Example taken from "Chapter 2: Machine Tools and Their Controls," in *Modern Machine Shop 1988 NC/CIM Guidebook* 60 n. 8A (January 1988): 56-57.

Two key characteristics of a machine tool's MCU are whether it operates in an *incremental* or *absolute* fashion, and whether it uses a *closed* or *open loop* system. In an absolute MCU system, each cutter movement is based upon a coordinate address relative to the origin. Incremental MCUs, however, direct the cutter tool from its previous position. Today most MCUs can be adjusted to either system.

In the more prevalent closed loop system, program commands in the MCU are compared with data from feedback devices to measure the disparity between the actual and desired cutter location. The cutter is directed to move until this disparity is zero. A variety of feedback devices are used in NC machine tools, such as linear scales, lasers, rotary resolvers and optical encoders. Open loop controls operate without feedback mechanisms and have gained more acceptance as the controllability of machine tool motors has improved. It is argued that less expensive and more easily maintainable controls can be built using open loop systems, with little cost to machining accuracy using modern motors.

Steps in NC Machining

The process of numerical control begins with the *part program.* Although advances have been made in computer-aided design that utilize computers for both designing parts to be machined and translating their coordinates into part programs, these stages are still largely completed by hand. However, it is common to use canned macros for most cutter path directions in part programs, merely supplying parametric values for each specific workpiece.

A part programmer converts a blueprint part drawing into a sequence of machining instructions based upon the rectangular coordinates of the cuts to be made. These instructions are written in NC processor languages such as APT, COMPACT, SPLIT, etc., which are processed to calculate the cutter coordinate data and generate a *Cutter Line (CL) file.*

Once the program is processed into coordinate instructions, it is run through a *post processor* to adapt the CL output to the specific machine tool and control unit being used. Because of the proliferation of different post processors, a growing practice is to convert part programs into *Binary Cutter Location* (BCL) directions that can be more readily exchanged among NC machines. BCL is similar to the concept of converting data into ASCII to export it among microcomputer packages.

Part programs are stored in five types of media: punched tape, punched cards, magnetic tape, diskettes, and direct data transmission over cable. Punched tape was

adopted as the industry standard and is still the predominant form today, using photoelectric cells or electronic "brushes" to sense the pattern of holes. Most MCUs are equipped with punched tape readers, even if other media can be accommodated. Floppy disks are gaining preference on shop floors, however, because they are less cumbersome and less readily torn or mutilated than tape.

Numerical control units can utilize several modes for processing part programs. In 1974, machine tools were introduced that used microcomputers to run the part processing from read-only or minimally modified part programs on floppy disk. This practice is called CNC, *Computer Numerical Control.* Another popular method is to share mainframe computing capabilities among many machine tools, downloading the processed part program directly to the machines via cable or some other storage medium. This system is called DNC, *Direct Numerical Control.*

IV. NC MARKET PERFORMANCE AND STRUCTURE

Despite the fact that numerical control was devised nearly forty years ago, its diffusion has been a slow process. According to an International Trade Commission report, in 1976 only 1 percent of total U.S. machine tools were numerical control. By 1982, this figure reached only 2.2 percent.[1] These figures are somewhat misleading since they refer to number of units rather than value, especially since machining centers can replace several conventional machine tools. Additionally, many conventional machine tools have since been retrofitted with numerical control. Nonetheless, the slowness with which numerical control gained acceptance is remarkable.

Partly because of this slow acceptance, data specific to NC production are difficult to obtain. The majority of data in this section consequently refer to the machine tool production industry in its entirety--conventional and NC.

Industry Structure

Although mergers and acquisitions of machine tool builders have increased in recent years, the majority of firms are small, family-run establishments. A 1982 Census of Manufactures noted 1140 U.S. firms producing metalworking machine tools as their primary product, down from 1343 establishments in 1977.[2] About two-thirds of these firms have fewer than twenty employees, and most are located in the mid-West and New England regions--particularly in Ohio, Michigan, Illinois and New York.[3] The average number of employees per establishment is 77.[4]

However, this atomistic market structure may be changing. Over the 1977-82 period, the Justice Department noted 64 mergers, acquisitions and purchases of assets involving machine tool producers. Additionally, the number of mergers occurring in the future is expected to increase.[5] Changes in the industry's concentration are difficult to observe thus far. In 1977, the four largest metal-cutting machine tool producers accounted for just

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[1]ITC. *Competitive Assessment of the U.S. Metalworking Machine Tool Industry* (Washington, DC: U.S.ITC Publication 1428, September 1983): 2.

[2]ITC, p. 18.

[3]National Machine Tool Builders' Association. *1981/82 Economic Handbook of the Machine Tool Industry* (McLean, VA: National Machine Tool Builders' Association, 1981): 64-65. Also NRC. *Competitive Assessment of the U.S. Metalworking Machine Tool Industry* (Washington, DC: National Academy Press, 1983): 16.

[4]ITC, p. 19.

[5]Ibid., pp. 18, x.

22 percent of industry shipments. By 1981, the fifteen top firms produced 70 percent of the industry's shipments, with the remaining 1000+ producers accounting for 30 percent.[6] Additionally, a number of firms, particularly in sectors such as aerospace that require highly specialized machining capabilities, do design and build their own machine tools and controls.

Today the industry is marked by production and procurement arrangements with offshore producers, as well as an increased presence of foreign builders within the United States. This presence takes the form of production and assembly facilities, as well as distribution centers.[7]

The majority of U.S. machine tool builders offer narrow product lines and specialized equipment.[8] According to a 1983 ITC survey of machine tool purchasers, some foreign-made standard machine tools such as lathes and machining centers are perceived as being higher quality than U.S.-built ones--in terms of productivity, maintenance requirements, and design. However, U.S.-built machine tools for specialty applications such as aerospace, fabricated metals and transportation equipment, are perceived as being superior to their foreign counterparts.[9]

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[6]NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base* (Washington, DC: National Academy Press, 1983): 9.

[7]"Metalworking Equipment," *U.S. Industrial Outlook 1988* (Washington, DC: GPO, 1988): 23-2.

[8]NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 9. ITC, p. ix.

[9]ITC, p. xiii.

Machine Tool-Using Industries

The U.S. machine tool industry (SIC codes 3541 and 3542) provides other industries with the primary means to cut and form metal into both consumer and intermediate commodities--it is a *linkage* industry. Machine tools themselves are even used in the production of other machine tools. Although a relatively small industry in terms of annual sales, machine tool production is of crucial importance to the manufacturing sectors of our economy. And because of this essential role, technological developments in machine tool products can have a strong impact on productivity in other industries.

Table 4.1

NC MACHINE TOOLS IN USE IN U.S. METALWORKING INDUSTRIES

Industry Share of Units for the Periods 1982, 1976-78, 1967, and 1954-63

(in percentages)

USER INDUSTRY	1982	1976-78	1967	1954-63
Primary Metals Industries	2.6	1.6	6.3	7.6
Fabricated Metal Products	14.0	11.1	n/a	n/a
--Ordnance & Accessories	0.8	1.7	3.8	3.8
Nonelectrical Machinery	50.9	49.6	49.1	43.1
--Metalworking Machinery	11.4	11.5	13.0	13.7
--Special Industry Machinery	3.9	6.4	n/a	n/a
Electrical Machinery & Equipment	10.4	11.1	16.7	9.3
Transportation Equipment	14.8	19.5	19.6	24.0
--Aircraft, Engines & Parts	8.5	16.1	18.2	17.6
Precision Instruments	4.7	5.5	2.5	1.9
Other	2.6	1.6	2.0	10.3

Source: *NMTBA Handbook, 1981-82*, p. 261. OECD, *NC Machine Tools; Their Introduction in the Engineering Industries*, p. 45. "Summary of the 13th Inventory by Industry," *American Machinist & Automated Manufacturing* 127 n. 11 (November 1983): 118-119. No other inventories have been published to date.

Table 4.1 shows the major consuming industries of NC machine tools for four periods in which inventories were taken: 1954-63, 1967, 1976-78 and 1982. These percentages are of total units rather than value. Industries that use specialized equipment--such as aerospace, automotive and oil equipment production--probably account for a larger percentage of inventory value than those percentages shown above.

Within the U.S. market for NC machine tools, the largest consuming industry has consistently been nonelectrical machinery, including metalworking machinery. Transportation equipment, particularly aircraft and motor vehicles, has also been a significant purchaser of NC equipment, as have the producers of fabricated metal products. The Department of Commerce estimates that in 1978, 28-30 percent of the value of domestic machine tool orders were made by the automotive industry and 10-12 percent by the civilian aerospace industry.[10] These two industries as well as producers of oil and gas equipment accounted for a heavy surge in demand during the late 1970s, the direct result of retooling to produce new fuel-efficient vehicles and meet the growing demand for non-OPEC oil supplies.[11]

Cyclicality of the Industry

Because machine tools are a significant capital investment for industrial producers, the machine tool industry suffers from extreme fluctuations in sales, cash flow, profitability and employment. New machine tool orders are considered a lagging economic indicator since such capital investment decisions tend to follow demand swings in user industries.[12] The machine tool industry is thus susceptible to the accelerator effect in the domestic economy, and its swings in demand tend to be both longer than over business cycles and more extreme.[13] This instability has a profound impact on the industry's capital formation and its ability to attract manpower. Since overall world machine tool demand does not exhibit these same extreme oscillations, exports are considered to be an important means of smoothing out the industry's demand.[14]

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[10]NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 53. 1981 figure from ITC. *Competitive Assessment of the U.S. Metalworking Machine Tool Industry*, p. 37, and the Department of Commerce. *U.S. Industrial Outlook 1988*, Chapter 23, "Metalworking Equipment," p. 23-3.

[11]ITC, p. 116.

[12]National Research Council. *The U.S. Machine Tool Industry and the Defense Industrial Base* (Washington, DC: National Academy Press, 1983): 23.

[13]National Research Council. *The Competitive Status of the U.S. Machine Tool Industry* (Washington, DC: National Academy Press, 1983): 18-19.

[14]Ibid., p. 40.

Figure 4.1 below displays some of the cyclicality of U.S. machine tool shipments for the 1956-86 period, as well as NC shipment data for the 1964-86 period. Note that NC shipments roughly account for 20-30 percent of the value of total shipments. Low points in its cyclicality occurred around 1958, 1971-72, 1976 and most recently, 1982-83.

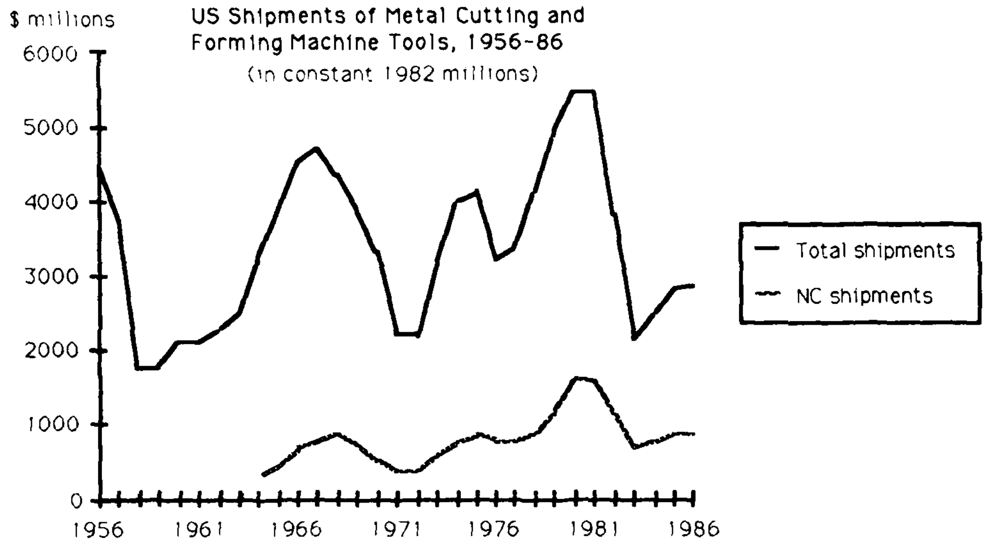

Fig. 4.1—Shipments of U.S. Machine Tools

Source: NMTBA, p. 100. Also phone conversation with an NMTBA economist, June 1988.

Capacity utilization dropped dramatically to a rate of 36 percent in the early 1980s, a time in which Japanese imports gained significant ground in the U.S. market.[15] In the mid 1980s, however, it rose to some extent. The Commerce Department estimates that machine tool production capacity has remained unchanged over the past few years, with current operating rates at about 50 percent of capacity.[16]

Employment

Cyclicality in machine tool purchases corresponds with cyclicality in that industry's employment (see figure 4.2). Employment peaked most recently in 1981 with 101,700

[15]ITC, p. x.

[16]"Metalworking Equipment," *U.S. Industrial Outlook 1988* (Washington, DC: GPO, 1988): 23-2.

workers. In 1987, employment stood at 64,300 workers.[17] The recent downturn in employment reflects lower levels of machine tools orders as well as the difficulty machine tool producers have expressed in their ability to attract skilled workers, since cycles in machine tool demand lead to the layoff of skilled workers in downturns, then labor shortages once better times return. Partly as a result of the need to attract skilled labor, wages increased from an average of $6.33 per hour in January 1977 to $10 per hour in October 1982.[18]

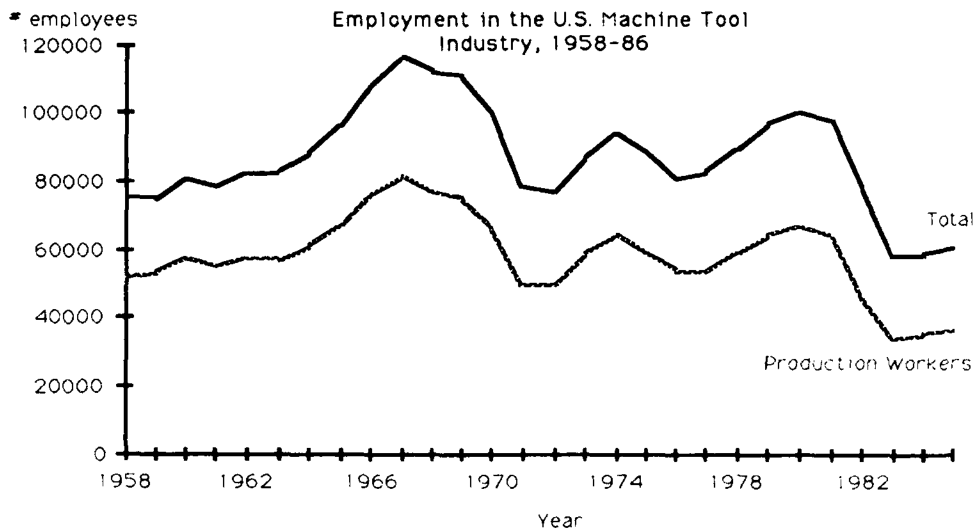

Fig. 4.2—Machine Tool Employment

Source: NMTBA, p. 233. "Metalworking Equipment," *U.S. Industrial Outlook 1988* (Washington, DC: GPO, 1988): 23-2.

The Commerce Department estimates that average changes in machine tool employment levels are over one and a half times those for durable goods employment.[19] Earlier this decade the NMTBA predicted a 17-20 percent shortage of skilled manpower relative to demand. This shortage is visible and occurred not only with the supply of machinists, but also that of manufacturing engineers, managers and computer

[17] Ibid.
[18] ITC, p. 21.
[19] *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 11.

specialists.[20] Additionally, the workforce of skilled machinists is aging, with an estimated average age of 58 years.[21]

Capital Investments and R&D Spending

Data from the Federal Trade Commission and the NMTBA suggest that over the 1975-81 period, machine tool builders enjoyed moderately healthy levels of profits and earnings on net worth. Profit and net worth levels rose steadily over the period and were generally higher than comparable figures for durable goods producers.[22] However, many U.S. manufacturers suffered losses in 1982 and 1983, corresponding with the economic recession and loss of domestic market share to foreign builders. Historically, profitability has also tended to be highly cyclic, as one might expect.[23]

Cyclic profitability and sales have made the financial community evaluate the machine tool industry as mature, with only moderate prospects for growth, and within a moderate-to-high risk investment category.[24] Concurrently, capital outlays of machine tool producers have lagged those of other industries. As a result, builders have generally tended to rely on a backlog order management system rather than increasing production capacity as other countries have done.[25] This is consistent with the finding that U.S. manufacturers require a longer lead time to delivery on average than do their foreign competitors.[26]

An ITC survey of U.S. builders found that machine tool manufacturers historically have had a difficult time generating capital, due to the industry's small size and cyclicality. Average debt-to-equity ratios of U.S. firms are less than 50 percent, while the same figures for major Japanese firms run 150-550 percent. Major European manufactures have debt-to-equity ratios of 30-120 percent.[27]

Unfortunately, this problem of access to capital occurs at a time when R&D expenditures are of growing importance--particularly among NC producers. As computer

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[20]*The Competitive Status of the U.S. Machine Tool Industry*, p. 23.

[21]Ibid.

[22]The 1975-81 average net operating profit on sales for the machine tool industry was 10.25 percent. Average earnings on net worth after taxes were 14.61 percent. Comparable durable goods industry figures are 7.34 percent and 13.22 percent respectively. NRC, *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 14.

[23]Ibid.

[24]Ibid.

[25]Ibid., p. 15.

[26]ITC, p. xiv.

[27]ITC, p. xi.

and electronics technologies have changed dramatically in recent decades, so has that of numerical control. Presently the level of R&D investments required to compete in the world NC market provides a significant barrier to entry for new competitors.[28] A standard CNC lathe design of 1974-75 was estimated to have a product lifetime of eight years. By 1978, a new design was growing obsolete in five years and by 1983, a design was expected to last three years.[29] A task force of machine tool experts estimated in 1980 that an NC or CNC control system has a real life of 3-5 years, due to the rapid obsolescence of computer hardware.[30]

R&D expenditure data are contradictory, probably because of ambiguous definitions of what they exactly include. A common estimation of industry-wide R&D spending is 1.5-1.6 percent of sales.[31] However, a survey conducted by the NMTBA came up with figures of 4.1-4.2 percent in 1981 and 1982.[32] It does appear to be the case that R&D expenditures rose over the 1970s and early 1980s, but the magnitude of that increase is not clear.[33]

World Market Shares and Foreign Competition

As mentioned earlier, Europe and Japan began commercial production of NC equipment 5-7 years after the United States. The UK and France were the first European countries to acquire the technology, producing NC machine tools in 1957 and 1958 respectively. Japan entered production in the early 1960s. However, commercial sales did not really take off until 1964 for Europe and 1965 for Japan.[34]

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[28]Jacobsson, Staffan. "Barriers to Entry into the Overall Cost Leadership Strategy," *Electronics and Industrial Policy: The Case of Computer Controlled Lathes* (London: Allen & Unwin, 1986): 90.

[29]Ibid., 89.

[30]G.P. Sutton. *The Technology of Machine Tools,Vol. I: Executive Summary* (Livermore, CA: National Technical Information Service, October 1980): 5.

[31]NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 14. Also *The Competitive Status of the U.S. Machine Tool Industry*, p. 49.

[32]NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 14.

[33]ITC, p. 32.

[34]OECD. *NC Machine Tools; Their Introduction in the Engineering Industries* (Paris, 1970): 36.

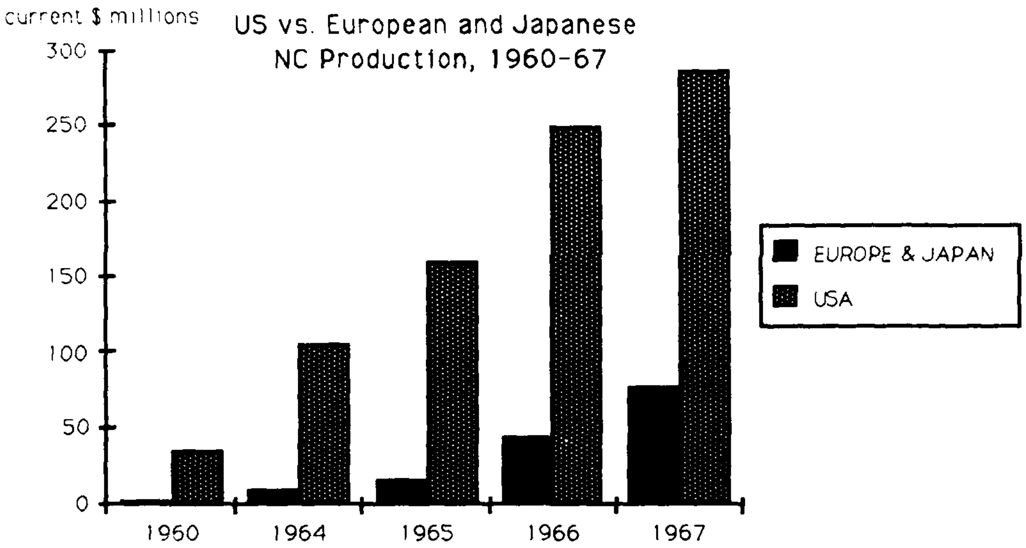

Fig. 4.3—Early NC Production

Non-U.S. countries include the FRG, France, Italy, the UK, Sweden and Japan. Source: OECD. *NC Machine Tools; Their Introduction in the Engineering Industries* (Paris: OECD, 1970): 36.

Figures 4.3 and 4.4 show the early volume of production and exports for the United States, Western Europe, and Japan. Note that although U.S. production clearly dominated that of other countries, the export market became competitive rather quickly. The U.S. was the single largest exporter over the 1960-67 period, but total non-U.S. exports surpassed the U.S. volume by 1966. This is undoubtedly due to the fact that much of the U.S. output was consumed by domestic industry.

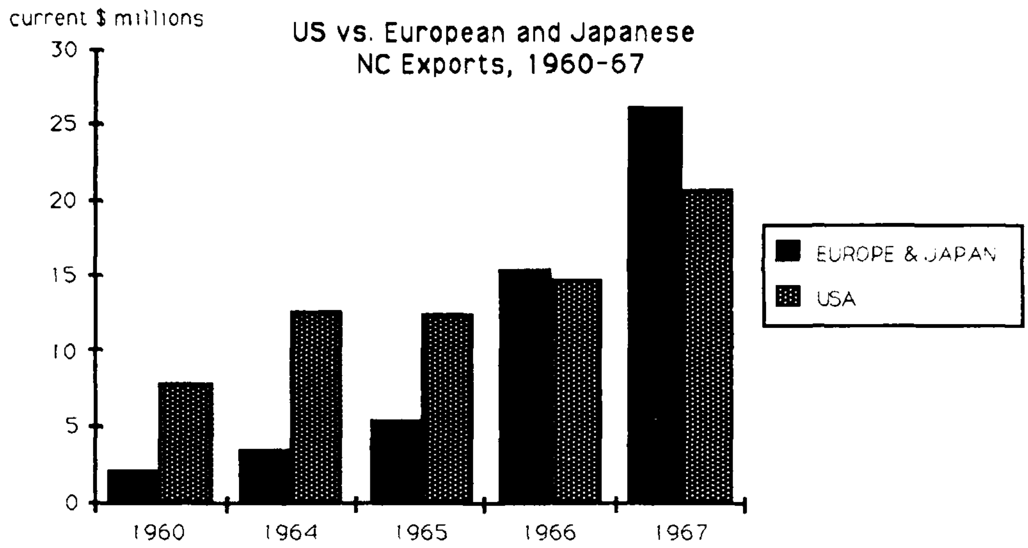

Fig. 4.4—Early NC Exports

Non-U.S. countries include the FRG, France, Italy, the UK, Sweden and Japan. Source: OECD. *NC Machine Tools; Their Introduction in the Engineering Industries* (Paris: OECD, 1970): 36.

Until the mid 1970s, the United States continued to be the world leader in value and volume of production and technology.[35] During the late 1970s and early 1980s, the U.S. and West Germany were closely tied in terms of machine tool production value. But by 1981-82, Japan surpassed all major producing nations to become the world leader.[36] Its growth surge has continued, and by 1986 Japan's production was 24 percent of total world output, compared with 18 percent for the FRG, 13 percent for the USSR and 9.5 percent for the U.S.[37]

It was not until 1978 that the United States experienced a trade deficit in machine tools.[38] Since that year, the import share of the U.S. market has continually increased, accounting for 51 percent of apparent consumption in 1986. In 1987, the primary sources

[35]Ken Gettelman. "Machine Tool Technology: The March Presses On," *Modern Machine Shop* 60 n. 9 (February 1988): 90.

[36]ITC, p. ix.

[37]Joseph Jablonowski. "Soviets Still Lead in Machine-Tool Consumption," *American Machinist & Automated Manufacturing* 132 n. 2 (February 1988): 63.

[38]*U.S. Machine Tool Industry and the Defense Industrial Base*, pp. 24-25.

of U.S. machine tool imports were from Japan (52 percent), the FRG (16 percent), Italy (6 percent), and Taiwan (5 percent). Leading export markets for U.S. machine tools were Mexico (16 percent), Canada (14 percent), Japan (9 percent), China (8 percent), UK (7 percent), and the FRG (6 percent).[39]

Figure 4.5 below shows 1986 world data on machine tool production and trade for the top ten producing nations. Total world production amounted to $28.89 billion, with total world imports of $10.9 billion and total world exports of $13.4 billion.[40]

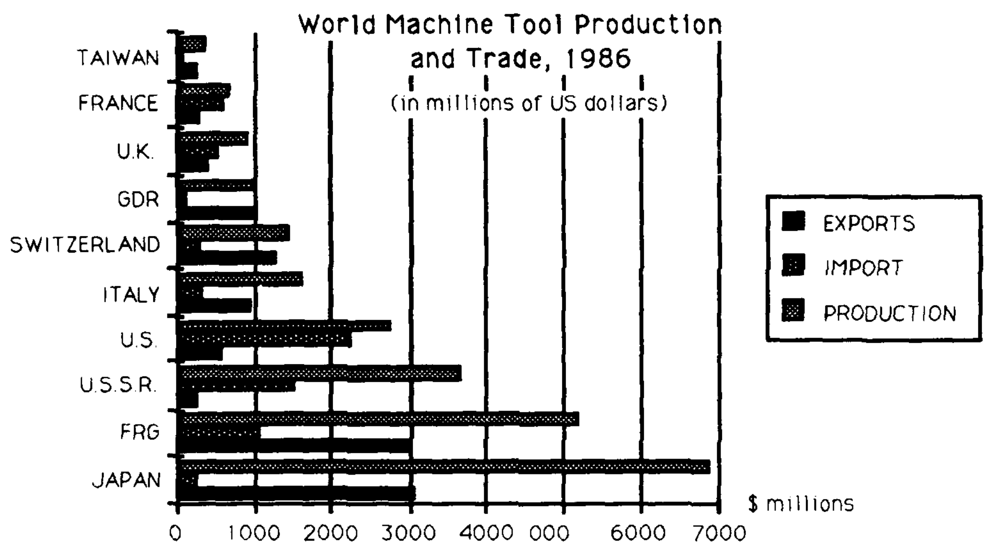

Fig. 4.5—1986 World Machine Tool Production and Trade

Source: *Joseph Jablonowski. "Soviets Still Lead in Machine-Tool Consumption," American Machinist & Automated Manufacturing* 132 n. 2 (February 1988): 63.

In a study of CNC lathes, a category of standard commodity machine tools, Staffan Jacobsson attributes the phenomenal growth of Japanese production to its "cost leadership strategy."[41] The primary component of this strategy was the development of smaller,

[39] *U.S. Industrial Outlook 1988*, p. 23-3.

[40] Jablonowski, p. 63. Total world import and export figures differ due to incomplete and conflicting data sources. The *American Machinist* database uses official country sources for these data when available, but must estimate figures for some countries based on various trade data.

[41] Jacobsson, pp. 47-66.

lower-performance machine tools that better suited the needs of medium-to-small size manufacturing firms. This product niche became relatively standardized, and Japanese firms were able to increase their production volume and benefit from economics of scale. These standard NC machine tools sold well in the relatively fragmented Japanese industrial market, and then spread to the world market.[42]

The United States machine tool industry was susceptible to an encroachment of imports in the late 1970s because of its own backlog of orders. U.S. machine tool demand grew significantly during this period, and U.S. production rates and capacity were insufficient to meet the demand. Imports benefitted from their shorter delivery time, lower costs for raw materials and labor, and lower product prices.[43] In the early to mid 1980s, import penetration was perpetuated by these factors as well as the strong dollar and growing familiarity with foreign products. Furthermore, Jacobsson argues that the U.S. builders did not adjust their production to changing consumption patterns towards microprocessor-controlled units.[44]

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[42]Ibid., pp. 47, 52.
[43]ITC, pp. 97-98.
[44]Jacobsson, p. 80.

V. THE U.S. GOVERNMENT'S METHODS OF INTERVENTION

As previously outlined, the Air Force had a pivotal role in NC, both financing the original contract for its development and procuring many of the first NC machine tools. However, some analysts argue that the DoD's central role led the machine tool industry "astray," inducing machine tool builders to focus on production for military applications at the expense of the more commonly used commodity tools.[1] This section analyzes the military's forms of support for the industry to shed light on these allegations. Alternatively, Section 6 looks at how military spending may have been used in an industrial policy capacity.

According to an OECD study on the growth of NC, numerical control was originally a less profitable venture in Japan and Western Europe than in the U.S. The combination of relatively high wages, a strong conventional machine tool industry, growing electronics, computer and aerospace industries and capital goods production in medium-size batch runs contributed to NC's relatively quick growth in the United States.[2] By the mid 1960s, however, both Japan and European nations outpaced the U.S. in growth rates of commercial NC output.[3] The OECD study suggests that the U.S. military industrial emphasis may be somewhat to blame for the industry's slowdown. It states that in the United States "over thirty percent in number and close to forty percent in value of NC machine tools are used in industries where economic considerations are not always the determining factor in the choice of equipment."[4]

To quote Seymour Melman, long a critic of the U.S. defense industrial base, "Military organization advances *militarily relevant* technology."[5] That is to say, he believes that civilian technologies do not benefit from military R&D. But how precisely might military support for an industry "misdirect" it from commercial applicability?

Two criteria come to mind in order for military industrial support to damage the civilian economy. First, the government's technological emphasis must have had little to

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[1] See for examples, DiFilippo, Anthony. *Military Spending and Industrial Decline: A Study of the American Machine Tool Industry* (New York: Greenwood Press, 1986). Also Nobel, op. cit.

[2] OECD. *NC Machine Tools; Their Introduction in the Engineering Industries* (Paris, 1970): 10.

[3] Ibid.

[4] Ibid., p. 46.

[5] *Pentagon Capitalism: The Political Economy of War* (New York: McGraw-Hill, 1970): 168.

no civilian use, thereby providing an opportunity cost "drain" on resources. Second, firms must have somehow disregarded civilian applications for their output, whether due to market structure and barriers to entry or poor management decisions. The first criterion puts direct blame on the military insofar as it diverts resources from civilian application and/or drives up the price of R&D inputs. The second, however, reflects management and market structure characteristics of the industry, typically not manipulated by the military.

One could make an argument in terms of counterfactuals, or "what might have been" in the absence or redirection of military investments. This tactic is taken in Section 7. Counterfactuals aside, however, it is a difficult case to be made that U.S. military investment in NC has damaged the machine tool industry. Numerical control technology is today widely applicable to civilian industries, although Air Force directed specifications may have induced industry standards that are not the best in commercial terms. However, according to an ITC study, Air Force-funded programs for the machine tool industry "have direct application in nondefense production."[6] And the majority of U.S. machine tool output is used within nonmilitary applications. Firms in the U.S. would be terribly remiss to disregard the technological and commercial needs of such a large sector of machine tools sales.

Early Military Support

In the period 1949-59, the U.S. military spent at least $62 million on NC R&D and its diffusion to manufacturing industries, or about $232 million in 1982 dollars.[7] According to one source, MIT and the Air Force tried to convince machine tool manufacturers and the aircraft industry to invest in this new technology, but met little acceptance. Only one company, Giddings and Lewis, privately financed R&D in NC prior to 1953.[8] After 1955, however, the AF Air Material Command changed its specifications for machine tool stockpiles from tracer technology to NC. Additionally, the Air Force financed the purchase, installation and maintenance of more than 100 NC machines in the facilities of prime and subcontractors, valued at $35 million, or $131 million in 1982 dollars.[9]

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[6] ITC, p. xi.

[7] Noble, p. 25. For purposes of comparison with figure 5, this figure was converted to 1982 dollars by using an average GNP deflator over the 1949-59 period.

[8] Ibid.

[9] Ibid. Also Comptroller General of the United States. *Numerically Controlled Industrial Equipment: Progress and Problems* (Washington, DC: U.S. General Accounting Office (GAO), 24 September 1974): 11.

In the late 1950s, the Air Force selected APT as its standard NC programming language in conjunction with the Aerospace Industries Association. However, numerous other languages have emerged within the machine tool industry, many of which are proprietary. APT is an extremely flexible language that can be used with most any machine tool. However, some have pointed to the proliferation of languages as evidence that APT's disadvantages--particularly the complexity of programming in it--are substantial.[10]

Military procurement accounted for the largest portion of NC sales in the early 1950s, but was outpaced by sales to private firms in the 1960s (see figure 8). Some of this equipment was placed in government-operated facilities in each of the three branches of the military, as well as other defense agencies, the Atomic Energy Commission, NASA, and the General Services Administration. However, the majority of government-purchased NC units were placed in contractor facilities, both privately owned and government-owned, contractor-operated (GOCOs).[11]

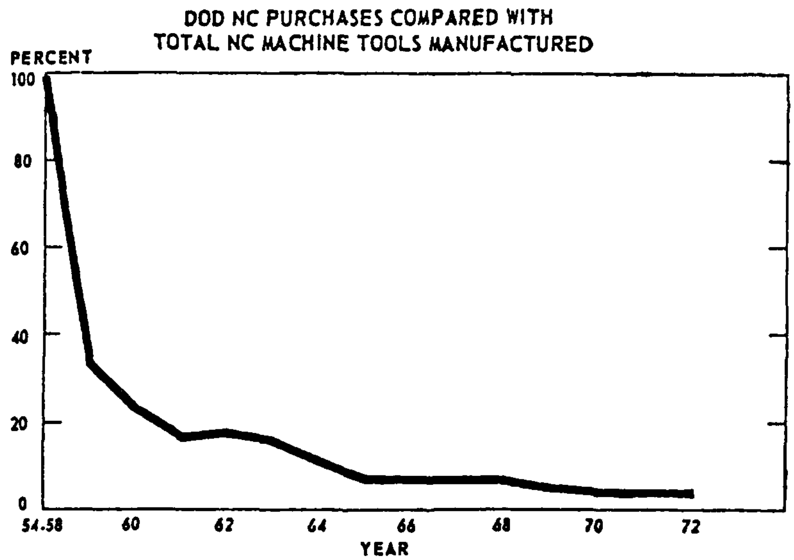

Fig. 5.1—Percent of Early NC Purchases Attributable to the DoD

Source: Comptroller General of the United States. *Numerically Controlled Industrial Equipment: Progress and Problems* (Washington, DC: U.S. GAO) 24 September 1974): 11.

[10]Noble, p. 27.
[11]GAO. *Numerically Controlled Industrial Equipment*, p. 9.

Early NC equipment was expensive and bulky, as well as complex to maintain. Part programming was a difficult process because of development "bugs" in early NC languages and the newness of computer programming. However, the U.S. military, particularly the Air Force, found several advantages in NC including:

- higher productivity and reduced machine downtime;
- faster uptime for machining jobs;
- more uniformity of parts and better machining accuracy;
- reduced need for machine tool parts inventories.[12]

However, as two GAO reports noted in the early 1970s, the military's use of NC machine tools in government-owned and operated facilities was not always managed well. Some NC machining jobs completed in DoD facilities could have been handled at less cost in private shops, sometimes using conventional machine tools. Additionally, government facilities tended to underuse NC capacity, its major cost advantage over conventional machinery.[13] These observations support the claim that the driving force behind equipment choice was not necessarily commercial concerns.

Military procurement of all types of machine tools accounted for only about 3.5-4 percent of domestic orders in 1978 and grew to 4.5 percent in 1981. As of 1982, the DoD owned a total of 63,148 conventional and NC machine tools, 86 percent of which were at least 20 years old.[14] Interestingly, the ITC found that U.S. military services have procured a number of machine tools from foreign countries in recent years. The majority of these purchases were made because foreign builders offered the lowest bid, best met military specifications, and/or had signed Memoranda of Understanding exempting them from Buy American clauses.[15]

Indirect purchases by defense contractors bring the percent of military-related machine tool purchases up to about 6 percent in 1982, according to the Commerce Department's Bureau of Industrial Economics (BIE). Data Resources, Inc. (DRI), estimated DoD and contractor purchases of machine tools to be 20 percent of total domestic machine tool

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[12] Ibid., p. 7.

[13] Comptroller General. *Use of NC Equipment Can Increase Productivity in Defense Plants* (Washington, DC: GAO, 26 June 1975): 6-18, 54-57.

[14] "13th Inventory of Machine Tools," *American Machinist & Automated Manufacturing* 127 n. 11 (November 1983): 115.

[15] ITC, p. 37.

consumption.[16] The DRI figure was estimated for the NMTBA and includes all indirect DoD supplier links, as well as contractor "induced capital" investments in machine tools due to government contract awards.

Recent Forms of Department of Defense Assistance

Because of the extensive use of machine tools in the manufacture of defense equipment, the three branches of the armed services are concerned about the modernization of production technology. The primary means of administering R&D and modernization assistance is through the joint services Manufacturing Technology (ManTech) program based at Wright-Patterson AFB.

ManTech was responsible for administering the Air Force's NC development contract and for the initial purchases of NC machine tools in the 1950s. As noted earlier, the Air Material Command at Wright-Patterson changed specifications for stockpiled machine tools from tracer-controlled ones to NC in 1955.[17] It was also the ManTech program that worked in cooperation with he AIA to establish APT as the defense industry standard for programming languages.[18]

ManTech does not itself purchase capital equipment anymore. Rather, its role is to provide seed money for manufacturing technology projects whose feasibility has been demonstrated and to help disperse resulting technologies throughout the industry. Its means of dispersal are through its *Manufacturing Technology* journal, National Technical Information Service documents, and the Defense Technical Information Center.[19] Recently ManTech awarded a $5 million per year matching grant to the National Center for Manufacturing Sciences, an 80-plus member consortium of machine tool and numerical control builders, for the development of new manufacturing technologies.[20] ManTech program funding levels for fiscal years 1978-88 are shown below.

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[16]Both BIE and DRI figures are from the *U.S. Machine Tool Industry and the Defense Industrial Base*, p. 53.

[17]Noble, p. 25.

[18]ITC, p. 38. Also Noble, p. 26.

[19]ITC, p. 38.

[20]"Air Force/Manufacturing," *Early Bird* wire news (2 June 1988): 6.

Table 5.1

MANTECH FUNDING LEVELS, FY78-88

(in current millions)

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Total	118	126	139	156	209	166	166[e]	166[e]	198	124	149[r]

e estimated from aggregate figure

r requested

Source: ITC, p. 38. NRC. *The U.S. Machine Tool Industry and the Defense Industrial Base*, p. 57. Also "Redo ManTech, Says Panel," *American Machinist & Automated Manufacturing* (September 1987): 129.

In 1987, the ManTech program received strong criticism from a National Research Council panel organized to review DoD's efforts at technology support. The panel found that in 238 multi-year projects in 1985-86, ManTech tended to focus on cost-reduction rather than the creation of new technologies, and the majority of projects focused on narrow technical objectives for a single product or facility.[21]

In addition to ManTech, the DoD maintains a general reserve of capital equipment to maintain industrial readiness. The Defense Industrial Reserve includes a stockpile of machine tools which are held for use in the more than 100 government-owned industrial plants and maintenance facilities, some of which are contractor operated. This reserve is composed of general purpose metal-cutting and forming machine tools.[22] In 1982 the reserve's total industrial plant and equipment amounted to 20,970 units (of machine tools and other equipment) with an acquisition cost of $430.5 million. Machine tools are also loaned from the general reserve for free use in nonprofit training facilities under what is known as the "Tools for Schools" program.

Finally, in 1982 the Defense Production Act authorized the Machine Tool Trigger Order Program. This program attempts to reduce the lead time for machine tool delivery in times of mobilization. It operates by organizing stand-by purchases by the Federal

[21]"Redo ManTech, Says Panel," *American Machinist & Automated Manufacturing* (September 1987): 129.

[22]ITC, p. 39.

Government from participating machine tool builders. The government acts as intermediary--finding buyers for the ordered equipment and taking on risks that would normally be borne by the builders themselves. The estimated dollar value of such stand-by agreements over the 1982-85 period is $1.5 billion.[23] The Federal Emergency Management Agency (FEMA) holds the overall responsibility for this program.

Non-DoD Agency Assistance

Three other government agencies actively assist the U.S. machine tool industry: the National Science Foundation (NSF), the National Bureau of Standards (NBS), and the Export-Import Bank (Eximbank).

The NSF supports research into manufacturing technology primarily through its Production Research Program, as well as its Industry/University Cooperative Research Program, the Innovation Process Research Program, and the Small Business Innovation Program.[24] The NSF's goals of its support are to advance research leading to higher manufacturing productivity and to ensure the training of larger numbers of manufacturing engineers for universities and industry. NSF Production Research Program funding levels for fiscal years 1980-84 are shown below. Data on funding levels of other NSF programs were not available.

Table 5.2

PRODUCTION RESEARCH PROGRAM FUNDING, FY80-84

(in current millions)

1980	1981	1982	1983	1984
2.3	2.8	3.1	3.5	4.6

Source: ITC, p. 41.

The NBS National Engineering Laboratory operates the Center for Manufacturing Engineering (CME) to support innovation and productivity in discrete-parts-manufacturing industries. The CME is charged with developing technical data on

[23]Ibid., p. 40.
[24]Ibid., p. 41.

manufacturing processes, as well as developing standards in manufacturing engineering, automation and control technology, industrial and mechanical engineering. NBS programs have also been involved in the standardization of control interfaces for CAD/CAM systems. Additionally, the CME runs the Automated Manufacturing Research Facility, an operating FMS system completed in FY86 in Gaithersburg, Maryland. This facility is made available to both industry and universities for nonproprietary research on manufacturing methods. CME funding levels for fiscal years 1982-84 are shown below.

Table 5.3

CENTER FOR MANUFACTURING ENGINEERING FUNDING LEVELS

FY82-84 (current millions)

1982	1983	1984
5.6	5.4	5.8

Source: ITC, p. 43.

The Eximbank does provide the machine tool industry with some bank guarantees and loans to finance exports. However, cases are sometimes denied loans on the grounds that the machine tools will be used to build foreign commodities competitive with other U.S. products.[25] The National Resources Council has also alleged that Eximbank loans are too short-term or require too large of a minimum amount to facilitate most machine tool sales abroad.[26] At the end of 1982, active Eximbank cases received $167 million in support in the form of direct and discount loans, short and medium term insurance, and financial guarantees.

Other Forms of Governmental Intervention

Other forms of governmental intervention such as taxes, tariff and nontariff barriers, patent laws and antitrust statutes affect all U.S. industries in terms of their incentives toward R&D. For example, tax reforms in 1981 eliminated much of the inheritance tax

[25] ITC, p. 43.

[26] NRC. *The Competitive Status of the Machine Tool Industry*, p. 44.

burden on small family-run businesses, a characteristic of many machine tool builders.[27] However, the recent elimination of accelerated depreciation may affect both the demand for new machine tools within other user industries and among machine tool builders themselves. Two other forms of governmental involvement appear to be most prevalent: export controls of sophisticated technology to Soviet bloc nations and trade barriers.

As briefly introduced before, export controls are administered by the COCOM to restrict the shipment of goods to Warsaw Pact nations that might otherwise jeopardize Western security. Some members of the U.S. machine tool industry argue that U.S. controls are more strictly enforced than in other COCOM nations, and that sophisticated equipment is often available from non-COCOM exporters.[28] Presently, all machine tools for aircraft production, four and five-axis NC machine tools, high-precision NC machines and some control units are placed on the Department of Commerce's export Commodity Control List.[29] These categories account for much of the U.S. output that is perceived to be of higher quality than foreign counterparts--specialty machine tools.

The most obvious program of support for the machine tool industry in recent years has been President Reagan's May 1986 domestic action plan to revitalize the machine tool industry. This grew from a request by the NMTBA for the Department of Commerce (DoC) to open a Section 232 investigation. Such an investigation calls for an assessment of whether or not imports of machine tools present a threat to national security.[30]

Commerce uses two criteria to evaluate whether or not national security is jeopardized: 1) whether sufficient supplies of critical commodities can be obtained from domestic producers and reliable imports; and 2) whether or not imports have been a contributing factor towards domestic production shortages. In March 1986, Commerce concluded that these criteria were met in seven of eighteen product categories of machine tools including: machining centers, horizontal NC lathes, non-NC lathes, milling machines, NC and non-NC punching and shearing machines.[31]

Consequently, President Reagan sought voluntary restraint agreements (VRAs) for these product categories with Japan, Taiwan, Switzerland and West Germany. Taiwan and Japan signed VRAs with the United States in December 1986 for a five-year period

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[27]NRC. *Competitive Status*, p. 66.

[28]Ibid., p. 41.

[29]Ibid., p. 42.

[30]DoC. Section 232. *National Security Import Investigations Fact Sheet* (Washington, DC: Commerce Dept., 1986).

[31]Ibid.

beginning January 1987, limiting exports to the United States to 1981 market share levels. The FRG and Switzerland have refused to participate.

The Commerce Department estimated that with constant demand equivalent to that of 1985, the VRAs would increase domestic sales by 16,500 units worth $775 million over the five-year period.[32] It was believed that protection of the U.S. market would boost machine tool builder revenues sufficiently to revitalize industry investment into R&D and production facilities. It remains to be seen if machine tool VRAs will have an effect similar to that of quotas placed on Japanese automobiles earlier in the decade--raising Japanese and U.S. automaker profits at the expense of higher prices for consumers.[33]

Conclusions

Military funding has strongly affected the U.S. machine tool industry and its development of numerical control. Air Force contracts were responsible for NC development and the Air Force, in conjunction with the AIA, played a critical role in the selection of APT as the industry's standard programming language.

Today military sources of funding (such as the ManTech program) dwarf that financial support administered by non-military government agencies (such as NSF and NBS programs). And military-related procurement of machine tools has been estimated to constitute 6-20 percent of total domestic consumption. These policies as well as President Reagan's domestic action plan were initiated primarily out of national security concerns over surge production capabilities.

It is likely that military support for the U.S. machine tool industry directly contributed towards its relative advantage in specialty machine tools. These complex tools are commonly used in the aerospace and transportation equipment sectors of the economy--those of special interest to the military. However, proof of *damage* to the economy from military support is hard to find.

The majority of purchases of U.S. machine tools went to non-military sectors of industrial production, indicating that attention must have been paid to the needs of these industries as well. And within the wider U.S. economy, civilian aerospace and the automotive industries are also major consumers of more complex machine tools. The

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[32]DoC International Trade Administration. *Machine Tools Fact Sheet* (Washington, DC: DoC ITA, December 1986): 2.

[33]For more information on Japanese automobile VRAs, see Leslie Wayne. "Irony and Impact of Auto Quotas," *New York Times* (8 April 1984): 5-1, 12.

technology of numerical control developed with military financing has both military and civilian applications--it was not prevented from being used in civil industry.

VI. ECONOMIC ROLES FOR GOVERNMENT SUPPORT

As the Section 232 findings for the machine tool industry demonstrate, recent examples of government intervention are primarily justified by national security requirements. In the opinion of the Reagan Administration, the industry's present state cannot ensure an adequate supply of machine tools in times of emergency. Similarly, it appears that the Air Force's initial investments into NC were also justified on national security grounds. However, this section looks for an economic justification behind the government's interventions. Did government support benefit American society in terms of economic well-being?

The machine tool industry meets several criteria used within the popular literature on industrial policy when selecting economic sectors to be targeted with government assistance.[1] First, machine tool production is a linkage industry to the rest of the economy--therefore alleged to provide multiplied payoffs for the investment. But no special returns can demonstrably be associated with support to such sectors. It is only in the presence of some sort of market failure or negative intervention by the government that users of machine tools will tend to underinvest in their capital equipment.[2]

Another popular argument is that the U.S. should target those industries that face competition from foreign industries who enjoy significant assistance from their own governments. Evidence does suggest that Japan, Taiwan and machine tool builders in Western Europe have received special targeting and support.[3] This topic is not addressed in much detail within this paper, but is an area that deserves considerable research. However, much like the application of tariffs in trade, defensive countertargeting may simply distort investment decisions more drastically. And countertargeting may lead to investment into sectors marked by excess world capacity, resulting in relatively low returns to government investments.[4]

In some situations, government intervention may be appropriately used to counter the threat of a foreign monopoly over a technological innovation. Alternatively, government support can be used to create a world technological monopoly for itself and perhaps earn

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[1]For a thorough discussion of the economic fallacies generally used to support these criteria, see Paul R. Krugman. "Targeted Industrial Policies: Theory and Evidence," in *Industrial Change and Public Policy* (Federal Reserve Bank of Kansas City, 1983): 123-155.

[2]Krugman, pp. 128-129.

[3]See ITC, pp. 47-97.

[4]Krugman, p. 133.

economic rents on export sales. The United States was the first country to develop numerical control and dominated the export market until the 1960s. If few U.S. producers were competing for the export market during that period, it is likely that some monopoly returns were captured by the United States. However, the cost cutting advantages of numerical control were not readily apparent to many industrial producers; the substitute good of conventional machine tools probably limited the value of rents to be earned on NC.

The General Issue of Market Failure

Government assistance to an industry appears to be a cogent policy benefiting society when it is used in instances of market failure. These market failures may be created by a government to benefit its populace, as in the case of monopolizing a new technology. More likely, however, government intervention is used to overcome existing market failures that would otherwise provide incentives to underinvest in R&D.

Perhaps the most general form of market failure addressed by many advocates of industrial policy is the difference between social and private rates of return to a firm's R&D investments, signifying external economies to the investment. For some industries such as semiconductors, technological developments are rapid and product cycles are short, therefore economic rents to those innovations are relatively small, probably leading to underinvestment at a societal level.[5] As the product life of NC machine tools shortens, the same may be true for this industry.

External economies mean that the social benefits of introducing an innovation are greater than a company's private returns. This is primarily due to the public good nature of technology and the inability to enforce patents and payment of royalties. It is widely alleged that most innovations, whether product or process technologies, exhibit this disparity between returns. Therefore, it is argued, the government can and should assist firms in the reallocation of society's investments toward some forms of R&D.

Edwin Mansfield et al. estimated this alleged gap in a sample of seventeen industrial innovations, including the incorporation of a computer numerically controlled machine tool in the early 1970s and the use of a new component for a control system introduced in the late 1960s.[6] Private rates of return were found by taking the present value of revenues

[5]Krugman, p. 147.

[6]Edwin Mansfield et al. "Chapter 8. Social and Private Rates of Return from Industrial Innovations," in *The Production and Application of New Industrial Technology* (New York: W.W. Norton & Co., 1977): 144-166.

from each innovation less R&D costs incurred and profits the innovator would have earned on displaced products. Social returns were estimated to be the internal rate of return on consumer surplus from the innovation less profits of other products displaced by the new technology plus the profits of "copycat" innovations.

In thirteen of seventeen innovations in the sample, social returns were greater than private ones, including both technologies related to NC.[7] Furthermore, the gap between social and private rates of return was found to be greater for products rather than processes, the former of which is the category that included the sample NC technologies. Mansfield also noted that in 30 percent of his sample cases, private returns were so low that no firm would have otherwise made the investment, yet the public returns justified R&D spending.[8] This empirical evidence supports the claim that firms may have a disincentive towards R&D investment. Further study on this topic would include a more exhaustive search for other empirical estimations to corroborate or dispute Mansfield's findings.

Next we turn to several forms of market failure specific to the machine tool industry that may indeed justify intervention. These include: 1) positive externalities to civil production; 2) "leftover" capital equipment spillovers; 3) economies of scale in some sectors of machine tools; 4) dynamically inefficient competition; and, 5) problems associated with access to capital.

Spillovers to Civil Machine Tool Technology

This form of market failure is essentially the same as that described above in the discussion of Mansfield's findings. Spillovers are positive externalities to society resulting from a private investment, i.e., marginal social benefits from R&D that are greater than those marginal private benefits observed by the investing firm. If observable private returns are less than public returns, the firm will underinvest in R&D relative to the level that is socially optimal.

Initial NC machine tools were built under contract (presumably cost plus) with the Air Force, thereby limiting the appropriability of economic rents. Unfortunately, I was unable to uncover data on how the transfer of NC technology to machine tool builders took place, i.e., I do not know whether builders were charged a licensing fee by the

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[7]The estimated returns were as follows. Computerized machine tool innovation: 83 percent social return, 35 percent private. Component for control system: 29 percent social return, 7 percent private. Ibid., p. 157.

[8]Ibid., p. 158.

government to recoup R&D costs. Given that the military aggressively sought private interest in NC and met little of it,[9] I find it doubtful that much of a royalty was charged.

I believe a strong case can be made that spillovers exist in the machine tool industry by virtue of the fact that it is a *dual use* industry. Future research would look for the number of firms that initially offered NC machine tools to civil industry to determine if rents were earned on early non-military sales. However, the machine tool industry's unconcentrated structure, the availability of general computer technology during the period (directly affecting the ability to imitate controller designs), and the existence of a strong substitute for NC (i.e., conventional machine tools) strengthens the case that spillovers existed.[10]

Furthermore, users of early military-procured NC machine tools were often themselves involved in the civil economy. Civil aviation and transportation equipment producers with military contractor divisions probably had ample opportunity to observe these early machines. If information was shared among division managers, civil managers may also have had access to data on their procurement price. Such knowledge would correct the asymmetry of cost information often associated with new technology products between buyers and sellers.

Leftovers

This category is also a specialized form of positive externalities. Essentially the term leftovers is used here to describe the situation in which benefits are accrued beyond the value of the original military contract. In the case of NC, I hypothesize that Air Force contracts for its development and procurement probably resulted in benefits beyond their cost.

The first NC machine tools were given to contractors at no cost. The literature I reviewed suggests that this action was primarily a national security precaution, ensuring surge capability. Luckily, few such emergency situations have arisen. Instead, those original machines resulted in additional productivity gains and labor cost savings beyond their national security value. If those cost savings indeed occurred over the life of those first machines, they should be counted as societal benefits beyond the cost of industrial surge insurance.

Yet another related positive externality is the development of human capital under those first Air Force contracts. Insofar as initial contracts trained machine tool builders in

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[9]See the discussion on page 24 based on Noble, op. cit.

[10]Remember as well that Mansfield's data on the introduction of a CNC machine tool in the early 1970s estimated a 48 percent disparity between social and private returns.

the design of NC equipment, they created a pool of mechanical engineers and computer programmers whose skills were then available for further civil or military use.

Economies of Scale

Government intervention can be beneficial to society in a situation where an industry's producers are not able to achieve cost savings from economies of scale without sizable government procurements. For example, a government strategy of ordering a large lot of NC machine tools would unambiguously be good for society if the economy-wide cost savings from economies of scale outweighed the cost of government procurement.[11]

Interestingly, this form of market failure was one that was not corrected by the U.S. military's interventions in the machine tool market. For this reason, the topic better falls under Section 7, the discussion of counterfactuals. Here, however, I will provide some evidence that economies of scale exist for some categories of NC machine tools.

In the previously cited Jacobsson piece on CNC lathes, the author makes a strong case for scale economies. According to his estimates, the control unit of the machine accounts for up to 50 percent of production costs, less for more complex lathe designs.[12] Software development is the costliest portion of the control unit, and therefore significant economies of scale are evident. As with other fixed costs, the per unit cost of developing processor software falls as the number of units ordered increases. This was the market strategy used by the Japanese in commodity machine tools. Table 6.1 provides some estimates of the magnitude of scale economy effects on price, made by representatives of a Japanese control unit supplier and a European CNC producer.

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[11]This analysis uses the typical Kaldor criteria whereby it is assumed that if machine tool builders earn profits from their cost savings, they could be redistributed among society via taxes and transfers.

[12]Jacobsson, p. 91.

Table 6.1

PRICE ADVANTAGES IN CNC UNITS DUE TO INCREASED LEVELS OF ANNUAL DEMAND

(in terms of normalized prices)

Annual demand	Japanese control system supplier	European CNC lathe producer
1		1.0
50	1.0	
100		0.8
300	0.8	
500		0.7
700	0.7	
1000		0.6
2000	0.5	

Estimates made by representatives of a Japanese control unit supplier and a major European CNC lathe producer. Source: Jacobsson, Staffan. *Electronic and Industrial Policy: The Case of Computer Controlled Lathes* (London: Allen & Unwin, 1986): 93.

In an interview with a Southern California distributor for a major U.S. machine tool building firm, I also found evidence of economies of scale. The representative noted that his company has just begun building "focus factories" that will specialize in the production of machining centers and lathes. By introducing more capacity for large lot production of one commodity machine tool design, production costs are probably lowered dramatically.[13]

However, the Air Force has consistently focused on specialty rather than commodity machine tools, and therefore military intervention in the industry has not taken advantage of economies of scale. By definition, the demand for a specific type of specialty machine tool is not large. And as Jacobsson noted, when designs become more complex, a machine tool's control unit becomes a smaller proportion of cost, thus limiting potential

[13]Phone interview with an area representative for Cincinnati Milacron, May 1988.

scale benefits.[14] Because of the nature of aerospace and other military industrial production, specialty rather than commodity machine tools are needed. However, strict military performance specification requirements may only exacerbate the problem of lost scale economies.

Dynamically Inefficient Competition

Dynamically inefficient competition generally refers to an industry structure in which competition is likely to drive down prices to a level that provides no producer with a normal return on capital. Such a "sick industry" scenario exists in the presence of: 1) overcapacity relative to current and probable future demand; and 2) rigidities that prevent the reallocation of resources toward growth industries and technologies.[15] The problem can continue for a protracted period (even decades in the case of the U.S. railroad industry) when startup costs are high, since firms will see it in their benefit to continue production and recoup all variable and some of their fixed costs.[16]

The U.S. machine tool industry exhibits some of the symptoms of a "sick industry," due mainly to its historically atomistic structure and extreme cyclicality. If we generalize the ruinous competition model to incorporate R&D investment behavior, these symptoms become apparent. Each firm's decision to invest is similar to that of lowering prices. To a small family-run firm, the decision to invest in R&D appears to be an extremely risky proposition, especially when profit margins are low. First, the project may not succeed, and second, it may invite an endless spiral of technological competition. From society's point of view, however, the public rate of risk is low enough to warrant investment in new technologies. Again, underinvestment results in the absence of government intervention.

The financial conservatism of small family-run builders in the United States is renown. This behavior is reputedly because of the extreme fluctuations in demand and the lack of longer-term investment strategies among firm managements.[17] However, more research needs to be completed on the applicability of the ruinous competition model. For example, have profit margins traditionally been low? What is the relationship between capacity utilization and investment?[18] Is the industry instead plagued by a widespread

[14] Jacobsson, op. cit.

[15] F.M. Scherer. *Industrial Market Structure and Economic Performance* (Houghton Mifflin, 1970): 212.

[16] Ibid., p. 213.

[17] NRC. *The Competitive Status of the U.S. Machine Tool Industry*, p. 49.

[18] Because several sources drew attention to the use of backlog order management systems, overcapacity does not appear to be a consistent problem in this industry.

case of poor management practices? If the characteristics and behavior of this industry match those of a dynamically inefficient industry, then the Air Force's intervention may have worked to overcome the tendency of R&D underinvestment.

Financial Market Failure

This form of market failure is related to that of dynamically inefficient competition. According to the literature I reviewed, most machine tool firms are perceived to be in moderate-to-high credit risks by financial institutions (see Section 4, page 18). This perception is largely due to extreme fluctuations in demand. If the interest rates charged by banks are overwhelmingly high for firms, underinvestment will result. This problem is compounded by conservative management, who may assess the expected returns to an R&D project as being lower than a more risk neutral evaluation. Therefore, the definition of "overwhelmingly high" is subject to much dispute.

Evidence reviewed thus far does suggest that financial market failure has occurred in the U.S. machine tool industry. This would again imply that the military's investment in NC technology was a positive move. However, it is not clear that this form of market failure is equally applicable to today's industry structure. If firm mergers and acquisitions continue, larger machine tool builders may be better able to assume higher rates of risk, thereby redefining upward what rates are "overwhelmingly high."

Conclusions

We have seen evidence of some probable forms of market failure in the U.S. machine tool industry that would lead to underinvestment in R&D in the absence of intervention. Mansfield et al. estimated that a general disparity occurs between private and public rates of return; that a firm's returns on technological investment are typically less than social benefits. Other forms of positive externalities were observable: the absence of duplicative research on NC technologies for civilian application, increases in productivity enjoyed by users of early government-procured NC machine tools, and the training of personnel who may have been hired to produce civil NC equipment.

Additionally, the extreme cyclicality of machine tool demand and the historically atomistic industry structure may have led to additional forms of market failure: a "sick industry" attitude toward R&D investments probably restricted the industry's access to capital from the financial market. General underinvestment in both capital equipment and R&D is a problem that repeatedly appears in the literature about this industry.

With the exception of economies of scale, the Air Force's investment in numerical control appears to have positively benefited society. However, it is to the issue of lost opportunities to scale economies and other opportunity costs that we turn next.

VII. CONCLUSIONS—WHAT MIGHT HAVE BEEN

Students of history often find themselves theorizing on "what might have been," devising games of counterfactuals. This practice is somewhat pointless and unfair, since history can never be relived to test our hypotheses and we are benefited with hindsight. However, in the context of the military's involvement in economic policy, I believe it is useful to look at the opportunity costs of those actions taken.

As mentioned in this paper's introduction, the factual evidence on military support for the development of numerical control is ambiguous. As far as the military's goals are concerned, support for the U.S. machine tool industry has consistently been couched in terms of ensuring surge capacity. Military support has repeatedly emphasized technological development in the specialized rather than standard sector of machine tools, the former of which is of key importance to military production. As the OECD report cited earlier points out, economic considerations were probably not a primary concern. Rather, flexibility in manufacturing and increased productivity were more important.

It just so happens that the industry of concern to the Air Force was one that consistently was plagued by market failures resulting in low rates of R&D investment. Access to capital was limited by the industry's market structure and its extreme demand cyclicality. And positive externalities to technology limited the appropriability of returns to private R&D investments. Under these circumstances, we cannot say that military support for NC development was unambiguously bad. Furthermore, it may be the case that the United States was able to earn some monopoly profits on its early NC exports.

Some aspects of the history of numerical control would have remained unaffected by any form of government intervention in the domestic industry. For example, the current success of West German and Japanese machine tool builders is partly due to their industrial reconstruction after World War II.[1] These countries began the era of numerical control with a strong demand for machine tools to replace those that had been devastated by the war. The replacement cycle for this stock of equipment probably occurred in the mid 1970s to early 1980s--the time in which more advanced computer technology such as CNC units became available and affordable. The factor of timing was unavoidable for the Air Force.

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[1] Bernard Udis. "Book Review of *Military Spending and Industrial Decline* by Anthony DiFilippo," *Journal of Economic Literature* XXVI (June 1988): 690.

How then might we have rewritten history? First, there is the matter of our own technological timing. Numerical control's development was highly dependent upon the capabilities and affordability of computer technology. The Air Force and MIT found little private interest in developing NC, and the technology's commercial viability had to be guaranteed by sizable military procurements. Perhaps commercial interest would have been piqued if the Air Force had sought support a few years later--when control units were less bulky, less costly, and problems related to programming were easier to manage.

Further research on this topic should look for data on the first sales of NC equipment after major military procurements. Did the costs of producing NC machine tools fall significantly during the period? Were monopoly rents earned on the first exports of NC equipment?

A second counterfactual relates to the issue of military specifications and specialty machine tools. Given that the Air Force's goals were primarily ones of national security, it is understandable that its concern for machine tool technology was essentially only as a linkage to aerospace output. However, a generally healthy and profitable machine tool industry is also important for national security. Cultivating the industry's production towards high-performance equipment was at the cost of losing the profitable standard machine tool market, the product niche in which economies of scale are most evident. Based on the success of the Japanese, sales of standard two- and three-axis machine tools to medium- and small-size manufacturing firms can be quite profitable.

Finally, there is the question of how best to administer R&D assistance. Given that this industry has continuously underinvested in capital equipment and R&D, government support appears to have been a good thing. But might that support have been better utilized if it had been administered more evenly between military and non-military agencies? If one measures utilization by the mix of standard and specialty machine tool production capability in the economy , I tend to think so. If a strong tradeoff exists between commercial profitability and national security production capabilities in the U.S. machine tool industry, then perhaps we have overemphasized the latter. Within our political system, however, I believe it is often easier to win R&D financing for industries under the guise of national security.

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Articles

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Excellent summaries of the basics of NC (numerically controlled) technology and its operation. This was my primary source of information on the physics geometry of the technology and its evolution. This issue also includes a thorough listing of the producers of NC machines, parts and controllers.

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Books

DiFilippo, Anthony. *Military Spending and Industrial Decline: A Study of the American Machine Tool Industry* (New York: Greenwood Press, 1986).

A good review of this book was written by Bernard Udis in the June 1988 *Journal of Economic Literature* (pp. 690-691). The book is primarily a tirade on the influence of military spending on the civil economy. Its uses a socialogical approach and is quite one-sided.

Jacobsson, Staffan. *Electronics & Industrial Policy: the Case of Computer Controlled Lathes* (London: Allen & Unwin, 1986).

This is the author's economics Ph.D. thesis from the University of Sussex on the growth of CNC industries in three NICs (newly industrialized countries)--Korea, Taiwan and Argentina. It provided some very useful hypotheses about why the Japanese have grown to dominate the world market in machine tools. Additionally, Jacobsson offered cogent economic analyses of market structure forces in some of the major machine tool building countries, as well as a discussion of the role of governments in developing this sector of their economies.

Mansfield, Edwin, et al. *The Production and Application of New Industrial Technology.* New York: W.W. Norton & Co., 1977. See especially chapters 7, "The Diffusion of Numerically Controlled Machine Tools in Ten Manufacturing Industries," and 8, "Social and Private Rates of Return from Industrial Innovation."

Chapter 7 describes an economic model estimating the rate of imitation of an innovation (NC) in the machine tool industry. Provides some comparative data on rates of NC diffusion among its most prominent purchasing industries. Within Chapter 8 Mansfield and George Beardsley provide careful estimates of social and private rates of return to seventeen different industrial innovations (including a computer control system). This is a great example of careful theoretical and empirical work on the subject of government-sponsored R&D. The empirical results show that generally private returns tend to be smaller than returns to society.

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Committee on the Machine Tool Industry, Manufacturing Studies Board; Commission on Engineering and Technical Systems, National Research Council. *The U.S. Machine Tool Industry and the Defense Industrial Base.: An Agenda for Research.* Washington, DC: National Academy Press, 1982.

This report was the first in a series sponsored by the National Research Council to assess the health and wartime readiness of the U.S. machine tool industry. It provides limited background information on the industry's structure, a discussion of the specific defense needs that must be filled to serve U.S. national security interests, an agenda for further research on the topic.

Committee on the Machine Tool Industry, Manufacturing Studies Board; Commission on Engineering and Technical Systems, National Research Council. *The U.S. Machine Tool Industry and the Defense Industrial Base.* Washington, DC: National Academy Press, 1983.

This is the second in the National Research Council's series of reports about the defense readiness and health of the U.S. machine tool industry. It provides a thorough examination of recent restructuring that has occurred in the industry, as well as a discussion of how Department of Defense prime and subcontracts have affected the industry structure.

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